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Final Report to NASA Goddard Space Flight Center on NASA Grant NAG5-1244

"Superconducting Films for Single-Photon X-Ray Detectors"

p. 11

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1. Table of Contents

2. Abstract

We have completed initial development and testing of Nb-Ta-Al-AlOx-Al superconducting tunnel junctions for x-ray detection with high efficiency and high energy resolution. These devices utilize Ta as the x-ray absorber with "band-gap engineering" employed to have quasiparticles trapped into an Al trap film. Experimental results at T = 0.25 K show an energy resolution of 110 eV FWHM for 6 keV x-rays. Collected charge is typically in excess of 10×10^6 electrons per x-ray photon, which is higher than in almost all previous studies. A mechanical mask was used to shield the trap and absorber near the trap from x-ray absorptions.

3. Project Description

This program has received support from GSFC in recent years, and the goals and progress in past years was summarized in previous proposals. The goal has been to develop x-ray detectors which are based on superconducting absorbers, with aplication as detectors with areas up to 1 mm^2 in future designs. The best energy resolution obtainable is limited by statistical fluctuations in the detected charge, due to the quantized charge of the electrons. This best resolution is given by

$$E_{FWHM} = 2.35\,(E_x\,F\,\varepsilon)^{1/2},$$

where E_x is the energy of the absorbed x-ray, F is the Fano factor, and ε is the energy required to create a single charge. This resolution should be better than 10eV for 6 keV x-rays. This is significantly better than semiconductor p-n junction detectors.

At the outset of this research program, we had to define the materials and detection systems which would be optimal, and in addition, develop the fabrication methods (and equipment) to produce reliable devices. As of beginning of 1994, we have achieved sucess in this. We first review the longer term history, then our progress during the past year.

A. Summary of Results for past 5 years of Research Program

We wish to review first the overall plan we have followed on this program, as it shows the many developments which have taken place in this program.

Prior to Aug. 1992

- tried soft counterelectrodes (Sn, In, Pb) with Al base electrode - shown not to work (by Aug. 1991)
- developed Al-Al oxide-Al junctions, deposited in Varian evaporator -good IVs
- set up single-stage 3He system for Al junctions
- deposited Ta films at room temperature for calorimeters in Lesker sputtering system

by Feb. 1993

- added evaporation capability to Lesker system
- Ta absorber with Al/Al junctions, all made in Lesker system; good IVs

- magnetic shield gave BCS IVs and reproducible Fiske modes, at 0.38K
- stable dc amplification
- hot deposition of Ta, much work on optimizing junction fabrication
- no x-ray pulses

<u>by August 1993</u>

- observed pulses due to 5 MeV alpha particles
- voltage amplifier for pulses (useful only for higher temps, ≈ 0.38 K)
- established that B is < 0.1 G perpendicular to junction
- put x-ray (or alpha) source on rotating arm to allow clean tests of pulse origins
- tested Ta-Al interface
- developed plasma etch of Ta (had previously used wet etch with Fe-chloride)
- made new masks for junctions - numerous test structures, junctions requiring lower B field for I_c suppression

<u>by Feb. 1994</u>

- x-rays detected; energy resolution of 250 - 300 eV FWHM, with tail of pulses on high energy side, indicating that substrate events are suppressed, and that quasiparticle out-diffusion is negligible; 65 eV electronic noise with charge amp
- no quantitative modelling of pulse data yet
- set up two-stage 3He system; achieved 0.30 K with one stage; two stage operation not yet successful
- good junctions at 0.30 K : reproducible BCS IVs at low voltage (to $\approx 100\ \mu V$), reproducible Fiske modes at higher voltage, current rise at $V = \Delta \approx 180\ \mu eV$
- devices made with new masks; varied junction parameters, test structures

<u>by July, 1994</u>

- quantitative analysis and modelling of pulse data
- energy resolution of 110 eV FWHM at 0.25 K with a mechanical x-ray mask over trap region; operation at 0.25 K for > 4 hours
- resolved K_α-K_β peaks (see Fig. 4 below)
- tests of three different junction geometries, comparison to model calculations
- completion of M. Gaidis Ph.D. thesis

We find that the progress during this past three year period has been well directed toward the successful production and testing of robust superconductor structures as x-ray detectors. The specific progress during the most recent period follows.

B. <u>Recent Research at Yale: Aug. 15, 1993 to present</u>

We have now settled on a final device structure and materials. The design used is shown in Fig. 1. (Details are given in the Ph.D. thesis of M. Gaidis, June, 1994, Yale University.) The absorber is Ta (Δ = 700 μeV) with Nb as the wiring (Δ = 1400 μeV). An Al film forms the quasiparticle trap (Δ = 180 μeV). The tunnel barrier is Al oxide, which thermally cycles and is mechanically robust. We use lateral trapping primarily (as shown) because this provides faster cooling of quasiparticles to the Al gap edge than vertical trapping. Measurements were made at 0.3 K.

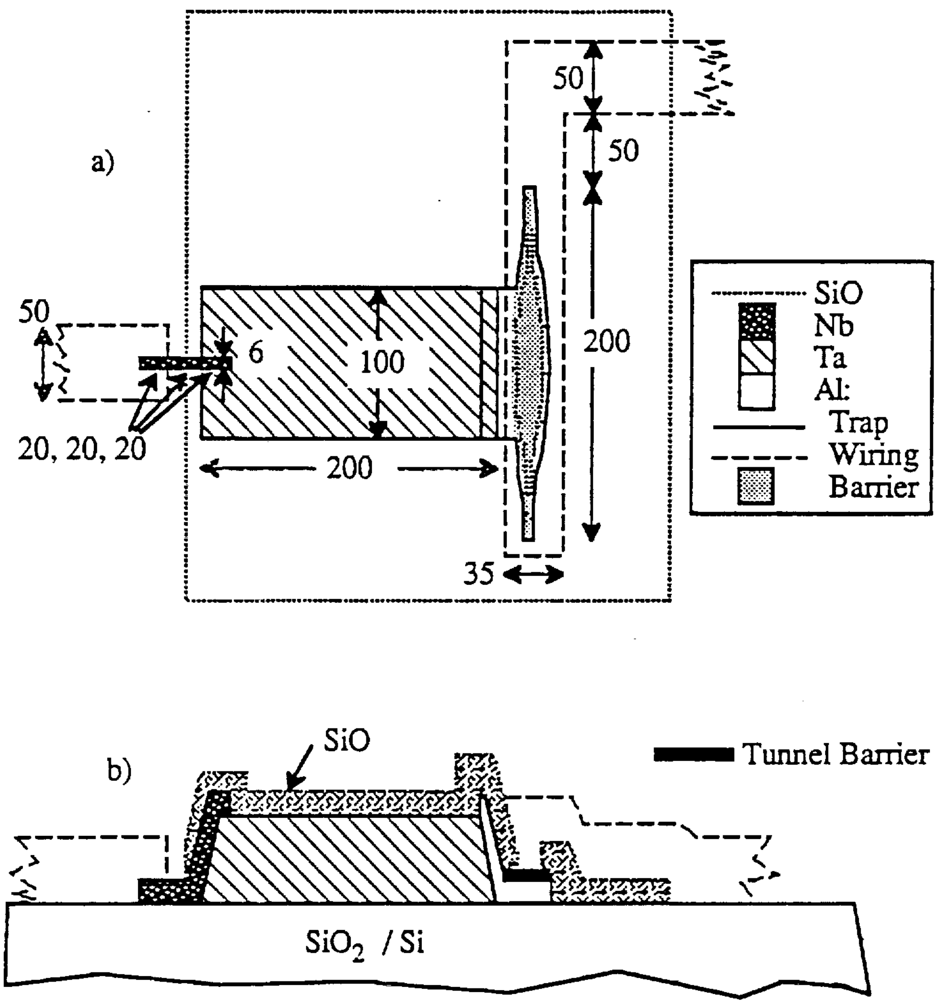

Figure 1. The specific device design used for most of this work's STJ x-ray detectors. All dimensions in microns. Film thicknesses are approximately: 6000 Å Ta; 1500 Å Nb; 1500 Å SiO; 2000 Å Al trap; 700 Å Al counter-electrode; and 4000 Å Al wiring. Top view (a) and side view (b).

The x-ray detection experiments have been carried out on three different devices. Device X-N93 has the geometry of Fig. 1. (The other two are variants of this.) The histogram of detected x-ray pulses is shown in Fig. 2. Since we expect that the collected charge is proportional to the photon energy, we can also read the x axis as 'energy'. The two peaks seen, at 5.7 and 6.3 x 10^6 electrons are due to the K_α and K_β emissions of the Fe^{55} source. Their location demonstrates the excellent linearity.

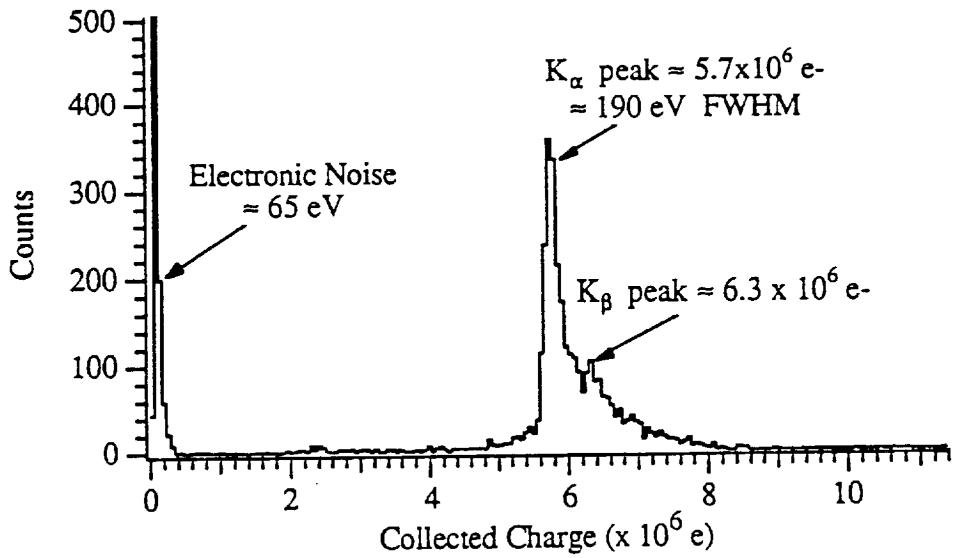

Figure 2 X-ray spectrum for device with trap masking. (X-N93, 3/15/94)

For the data shown here, a mechanical mask was used to cover the trap region and should prevent x-ray absorption in that region. We did this because in experiments without this mask, we saw a larger tail of pulses above the main (K_α) peak. We believe that excess phonon-generated quasiparticles in the Al are responsible for this peak, and that x-rays which are absorbed near the trap can generate more charge than those which are absorbed further away, as described next.

Fig. 3 gives a plot of pulse height *vs*. risetime for the data of Fig. 2. We see that the pulses with short risetime are those which have 'excess' energy. Thus, the fast arriving pulses are those which give the high energy tail. We believe that the region just next to the trap was not completely covered, and that the fast pulses originate there.

Another important feature in the data of Fig. 3 is the long risetime, ≈16 μsec, of the points with the 'right' charge values. This risetime is longer than expected from the sum of the trapping time (theoretical value ≈ 2 μs) and the tunnel time (theoretical value ≈ 3 μs). This may be due to a non-perfect interface between the Ta absorber and the Al films, or due to slow quasiparticle diffusion in the Ta absorber. These explanations can be checked in our device structures with a trap on each end of the Ta absorber. These have already been produced, and will soon be measured.

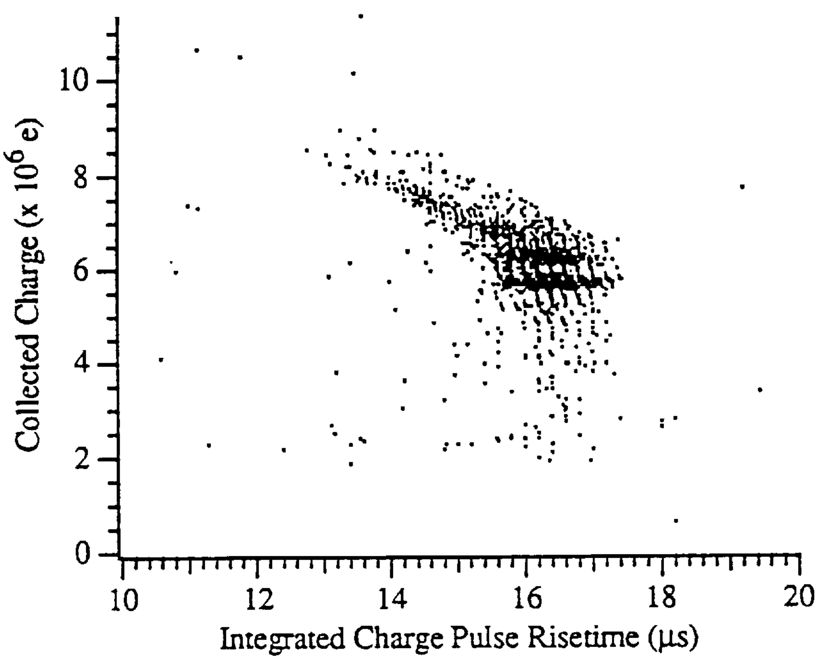

Figure 3 Pulseheight–risetime for the masked trap experiment. (X-N93, 3/15/94)

The computer simulations of the quasiparticle dynamics have been very useful in telling us where in the device the performance is being determined. We find, for example, that the quasiparticle losses in the Ta absorber must be rather small, less than 5 % or so, in order to explain the observed FWHM in Fig. 2. The two-trap geometry will allow us to determine the location of the x-ray absorption, and thus allow us to correct for losses in the absorber as the quasiparticle cloud diffuses into the two absorbers. With quasiparticle losses of only 5%, one can almost fully correct for these losses during diffusion to the traps.[1]

[1] H. Kraus et al., Phys. Lett. **231**, 195 (1989).

We have recently made measurements on a device like that of Fig. 1 at 0.25K. A copper mechanical mask covers all of the trap and much of the absorber. The results are significantly improved over those of Fig. 2 and 3. A energy FWHM of 110 eV is observed, and virtually no 'tail' of pulses at higher energy is observed, only the K_β peak. The electronic noise is about 71 eV, so the intrinsic detector resolution is about 84 eV. The risetime of the charge pulse is long, about 35 μs, and this may be due to slow diffusion of quasiparticles in the Ta absorber. We have improvements to make in the filtering of pulses (filters were not used for this run), and will be able to achieve improved statistics and likely better resolution in future runs.

We summarize other specific results here:

- the magnetic field required is only ≤ 9G, due to shaped junction design; this low field should avoid quasiparticle losses due to magnetic field-induced recombination in the trap and the absorber.
- $R_{dyn}/R_n \approx 2{,}000$; this ratio is large enough to allow the present electronics to function well; a larger ratio is desirable, and can be achieved with operation at lower temperatures. We find this ratio continues to increase as we cool down to 0.29 K.
- backtunneling from the Al counterelectrode is not significant, and is not the cause of the long risetime. This was determined by comparing devices with vias having different areas between the counterelectrode and the Al wiring layer.

The devices produced are robust and thermally cycle. They have characteristics which will allow their use as high resolution detectors, with modest improvements in performance.

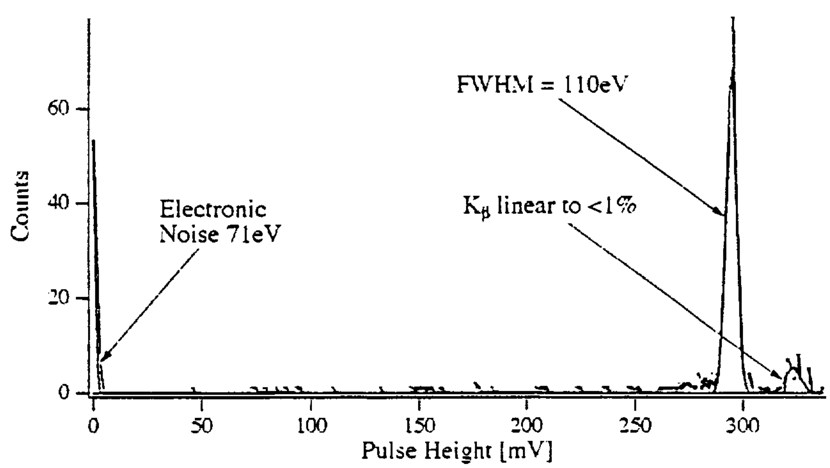

Fig. 4. Histogram of pulses from device XD94 at T= 0.248K, R_{dyn} = 2.7 kohm. Most of absorber and all of trap are masked from x-rays.

During fall, 1994 we focussed on preparing a paper to summarize our work, and the achievements with the single junction devices. This paper was submitted to Applied Physics Letters in Dec. 1994. During the preparation of this paper we worked to further understand the possible importance of backtunneling, and were able to consider the experimental results from a large body of experiments at various temperatures and device bias conditions. What we found is that backtunneling can sensibly explain many aspects of the data: the large collected charge, the longer-than-expected rise times, and (possibly) the temperature dependences of these quantities. However, the earlier experiments where we compared two different geometries, one with a large via and one with a small via, appeared to argue against backtunneling as being important. We are left with the conclusion that the experiments comparing devices with large and small vias proved only that the via size does not affect the backtunneling; backtunneling must be occurring, but due to less than perfect outdiffusion from the junction area. This will be tested in future experiments, but will require new fabrication runs. In any case, the analysis which was engendered by preparation of the publication proved very useful. We present in Fig. 5 the best device result at 0.3 K.

During fall 1994 we also evaluated the sources of the energy broadening of our x-ray pulses. We found that electronic noise of the amplifier by itself is small, of order 30 eV equivalent with a resistor at the input. This is not enough to explain the observed energy width, of order 100 eV FWHM. However, we also found that the noise of the amplifier with the junction connected was larger than 30 eV, and in fact approached the total noise we observe during experimental runs. Thus, we believe that the amplifier with junction is noisy, and that the intrinsic device noise may be smaller than 100 eV. We are working to track down and eliminate the source(s) of noise with the junction connected.

Since we anticipate the improvement of our device's energy resolution, or reduction of amplifier noise contribution, we also evaluated two oscilloscopes with better resolution than the present Hewlett-Packard scope, which has 8-bit resolution (approximately 30 eV per bin). The oscilloscopes made by LeCroy and by Nicolet were tested extensively, with a test resistor as a current source, a typical pulse shape, and the actual amplifier we now use. We found that the LeCroy scope with 10 bit resolution and with 'resolution enhancement' enabled, could provide resolution approaching 10 eV with noise free pulses on a resistive source and our own amplifier. The Nicolet scope, with 12 bit resolution, was even better, but was limited in bandwidth. Thus, both scopes are improvements over our present scope (and both are more expensive), but each had a particular strength.

Finally, during December 1994 the PI worked on designs for the hot-electron millimeter wave detector which is listed for activity in the renewal proposal submitted in 1994. A conclusion of that design work is that quasiparticles due to photon absorption will much exceed the thermal background if the detector is operated at 0.1 K and used in observations with moderate background. However, operation at 0.3 K in applications with moderate background, or operation at 0.1 K in low-background observations, can achieve the full, thermally limited performance. Thus, the detector design and operation must be matched to the particular observational goals.

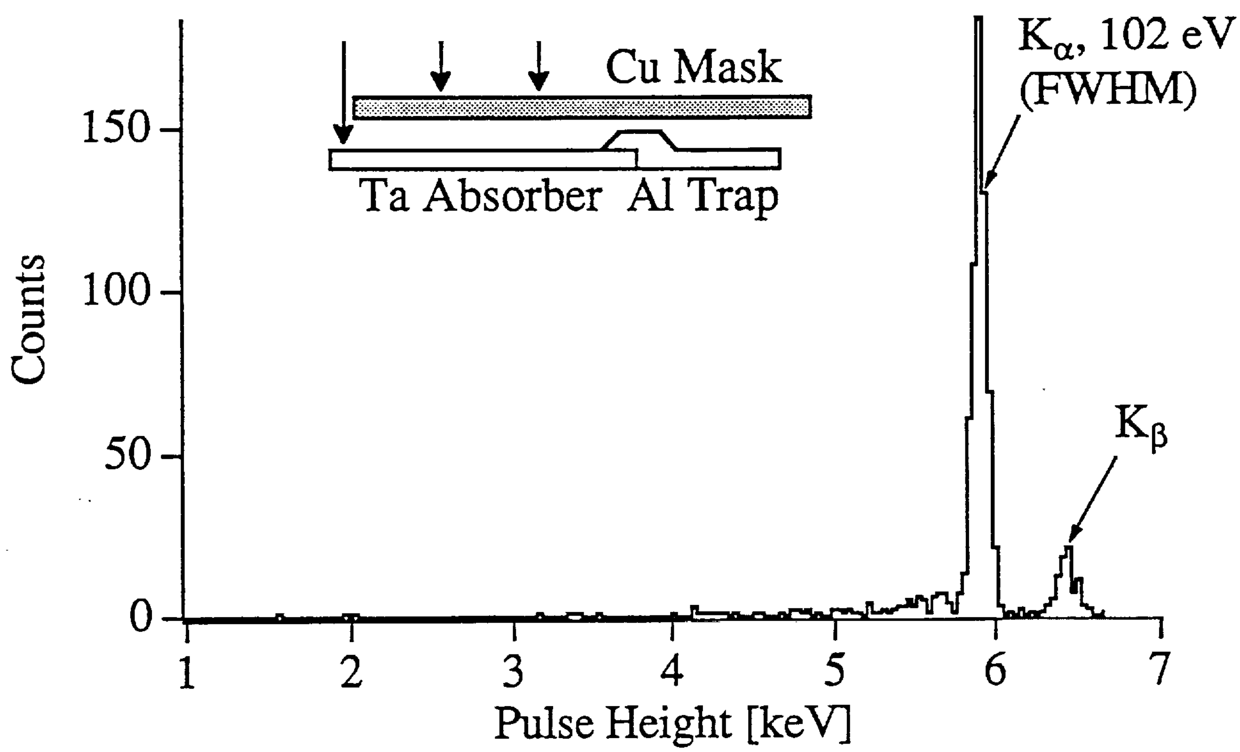

Fig. 5

Publications under this NASA grant

1. "Superconducting Al-Trilayer Tunnel Junctions for Use as X-Ray Detectors", M.C. Gaidis, S. Friedrich, D.E. Prober, S.H. Moseley, and A.E. Szymkowiak, IEEE Trans. Appl. Supercond. 3, 2088 (1993).

2. "Superconducting Nb-Ta-Al-AlOx-Al Tunnel Junctions for X-Ray Detection", M.C. Gaidis, S. Friedrich, D.E. Prober, A.E. Szymkowiak, and S.H. Moseley, J. Low Temp. Phys. 93, 605 (1993).

3. "A Superconducting X-Ray Spectrometer with a Tantalum Absorber and Lateral Trapping", M.C. Gaidis, S. Friedrich, K. Segall, D.E. Prober, A.E. Szymkowiak, and S.H. Moseley, submitted to Applied Physics Letters, Dec. 1994.

Additionally, presentations were made at the 1992 and 1994 Applied Superconductivity Conference, and at APS March meetings during the period of the grant. Various research seminars on this work were presented by the PI, M. Gaidis, S. Friedrich, and K. Segall at research laboratories and universities.